

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE 4-18-05		3. REPORT TYPE AND DATES COVERED Final Dec. 20, 2004 – Feb. 19, 2005
4. TITLE AND SUBTITLE Capacitive MEMS Microphone Optimized Research			5. FUNDING NUMBERS W911NF-05-C-0009	
6. AUTHOR(S) John F. McClelland and Michael Pedersen				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) MTEC Photoacoustics, Inc. 3507 Oakland St. Ames, IA 50014 Novusonic Corp., 17942 Pond Road, Ashton, MD 20861			8. PERFORMING ORGANIZATION REPORT NUMBER MEMS4-18-05	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER 47545.1-EG-DRP	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This report describes the initial design study of a project to develop a MEMS microphone optimized for photoacoustic signal detection. A MEMS based design has been developed with a predicted sensitivity 48 times that of current state of the art microphones and a 27 dB lower sensitivity to mechanical vibration. This new design is a modification of a commercial MEMS microphone currently in production. Arrangements have been made to produce a commercial prototype of this microphone for photoacoustic applications using a modification of the process that has been proven successful in the manufacture of millions of commercial telecom microphones.				
14. SUBJECT TERMS MEMS, microphone, photoacoustic spectroscopy			15. NUMBER OF PAGES 19	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

Form 298 (Rev.2-89)

Prescribed by ANSI Std. Z39-18

Standard

298-102

Final Report-CLIN 0001
**Capacitive MEMS Microphone Optimized
for PAS Applications**

Contract W911NF-05-C-0009

John F. McClelland
MTEC Photoacoustics, Inc.
and
Michael Pedersen
Novusonic Corporation

Foreword

This project was divided into two parts CLIN 0001, a MEMS Microphone design study, and CLIN 0002, a fabrication and testing task because the latter could not be budgeted in sufficient detail regarding MEMS foundry services to meet ARO requirements until the design and its review had been completed.

The project's key objective is to develop an MEMS microphone optimized for the needs of the LPAS program that will be available at the end of the project as a commercial prototype. This will allow LPAS teams to have a source of high performance microphones to be integrated into systems in Phase III. This is a demanding goal given that the considerable research investment made in MEMS microphone technology over the past 15 years has only resulted in one company, Knowles Acoustics, commercially producing MEMS microphones in large volume. Dr. Pedersen, a former member of the MEMS design team at Knowles, has been able to arrange to "piggy back" on the Knowles SiSonic MEMS microphone process which is the only practical way to achieve our goal under the budget and time restraints of the project. Hence the designs developed in this work are planned to be compatible with the SiSonic process which has produced millions of commercial devices successfully for other applications.

Table of Contents

	Page
Memorandum of Transmittal	1
Report of Inventions and Subcontracts (Form 882)	2
Final Report – Forward	3
Table of Contents	3
List of Appendices	4
Statement of the Problem Studied	4
Summary of Most Important Results	4
Publications	5
Scientific Personnel	5
Inventions	5
Bibliography	5
Appendix I	7
Report of Documentation Page (Form 298)	22

List of Appendices

Appendix I “On The Design and Dimensioning of a MEMS Condenser Microphone for Application in Photoacoustic Instrumentation”

Statement of Problem

CLIN 0001 addressed two problems: (1) designing an optimized MEMS microphone for PAS and (2) devising a means to fabricate the design as a commercial prototype given the project's budget and time constraints.

Photoacoustic spectroscopy (PAS) has advanced since its discovery by A. G. Bell in 1880 with each improvement in the component technologies that make up a PAS instrument. Especially notable are tunable laser sources, FT-IR spectrometers, and high sensitivity capacitive microphones which have allowed PAS measurements to play a growing role in analytical instrumentation. The next steps forward in PAS instrumentation in the important area of molecular analysis will be fostered by improvements in the tunability, power, energy efficiency, and lifetime of mid-IR lasers and in the sensitivity and vibration immunity of microphones which have never been properly optimized for the application.

Capacitive microphone optimization for photoacoustic signal detection has become an attractive and realistic goal due to the very significant gains in sensitivity and vibration immunity that are now possible with MEMS based devices. Such gains will impact current FT-IR PAS instrumentation by improving the signal-to-noise of PAS spectra and shortening measurement times. In the area of new PAS instrumentation, optimized MEMS PAS microphones will reduce the power requirements of mid-IR lasers currently being developed because the photoacoustic signal scales linearly with laser power. This will provide for longer device lifetimes and allow laser developers to concentrate on increasing the tuning range of their devices which is the most critical need for laser based PAS instrumentation.

Once the design is complete, producing a commercial prototype within the budget and time limitations of the project will require negotiating a teaming arrangement with a firm that has a MEMS microphone technology in commercial production that can be modified to meet PAS application needs.

Summary of Most Important Results

In order to develop an optimal MEMS microphone for photoacoustic instrumentation it is necessary to understand the underlying physics that governs the behavior of the device and the specific requirements imposed on the device by this application. Both of these factors are key elements in this project's MEMS device design study which is the blueprint for producing a commercial prototype in the second part of the project.

In this PAS application, signal-to-noise ratio is the overwhelmingly important parameter. Another important property is low sensitivity to vibration which is achievable in MEMS microphones due to a much smaller mass of inertia of the sensing diaphragm, when compared to state-of-the-art conventional measurement microphones. Through analytical and numerical calculations, it is demonstrated that a device can be designed with a sensitivity 45 times that of state-of-the-art conventional microphones, while at the same time reducing the vibration

sensitivity of the device by more than 27 dB. Such an improvement promises significant progress in the implementation of rugged, portable, high performance photoacoustic instrumentation for precise chemical and biological detection in the field. The use of MEMS technology allows the implementation of a pressure sensitive diaphragm with dimensions under 3x3 mm that far exceeds the sensitivity of a conventional 1/2" microphone diaphragm in a much narrower bandwidth suited for photoacoustic instrumentation. Since the bias voltage needed in the MEMS microphone is less than 1 V, the microphone can be easily biased by a small battery, and the sizing of the battery will depend more on the electronic detection circuit included with the microphone element. All simulations in this study were based on microphone designs already implemented in a proprietary commercial MEMS technology developed by Knowles Acoustics, currently the only successful manufacturer of MEMS microphones in large volumes.

The complete design study was presented at Photonics West 2005, San Jose, CA January 22-27, 2005 and will be published in the meetings proceedings by SPIE. The complete manuscript is attached in Appendix I.

The MEMS microphone design was reviewed with the engineering staff at Knowles Acoustics and found to be compatible with a modifications to Knowles SiSonic MEMS microphone process. Arrangements have been made with Knowles to have engineering runs made at their MEMS foundry to produce a commercial prototype which is the goal of the project.

Publications

Michael Pedersen and John F. McClelland, "On The Design and Dimensioning of a MEMS Condenser Microphone for Application in Photoacoustic Instrumentation", accepted for publication in Proceedings of Photonics West 2005, San Jose, CA January 22-27, 2005. See Appendix I.

Scientific Personnel

Dr. John F. McClelland

Dr. Michael Pedersen

Inventions

None

Bibliography

1. A. Rosencwaig, *Photoacoustics and Photoacoustic Spectroscopy*, Krieger Publishers, 1990.
2. L.L. Beranek, *Acoustics*, Acoustical Society of America, 1996.
3. S. Timoshenko & S. Woinowsky-Krieger, *Theory of Plates and Shells*, McGraw-Hill, 1970.
4. Brüel & Kjær product data sheet, *The Falcon Range 1/2" Microphones – Types 4188 to 4193*.

5. M. Pedersen, *A polymer condenser microphone realised on silicon containing preprocessed integrated circuits*, Ph.D. dissertation, University of Twente, The Netherlands, 1997.
6. Brüel & Kjær Technical Review, *Gas Monitoring*, No. 1, 1990.
7. US Patent no. 6,535,460, *Miniature broadband acoustic transducer*.
8. K. Wilcken and J. Kauppinen, "Optimization of a Microphone for Photoacoustic Spectroscopy", *Appl. Spectrosc.* **57**, 1087(2003).
9. J. Kauppinen, K. Wilcken, I. Kauppinen, and V. Koskinen, "High Sensitivity in Gas Analysis with Photoacoustic Detection", *Microchem. J.* **76**, 151(2004).

ON THE DESIGN AND DIMENSIONING OF A MEMS CONDENSER MICROPHONE FOR APPLICATION IN PHOTOACOUSTIC INSTRUMENTATION

Michael Pedersen^{*a}, John McClelland^b

^aNovusonic Corp., 17942 Pond Road, Ashton, MD 20861

^bMTEC Photoacoustics, Inc., 3507 Oakland Street, Ames, IA USA 50014

ABSTRACT

1. INTRODUCTION

To derive an optimum design of a MEMS microphone in any application (i.e. photoacoustic instrumentation), it is important to understand the underlying physics that govern the behavior of the device. In addition, one must have a good understanding of the specific requirements imposed on the device in the intended application. In the particular case of photoacoustic detection, signal-to-noise ratio is the overwhelmingly important parameter. Other parameters such as size and required operating voltage may be compromised to achieve the best possible signal-to-noise ratio. An important property, to be shown below, is the low sensitivity to vibration in MEMS microphones due to a much smaller mass of inertia of the sensing diaphragm, when compared to state-of-the-art conventional microphones.

In photoacoustic detection, a microphone is used to detect the minute thermal expansion/pressure wave generated in a gas due to molecular absorption, and subsequent release, of energy generated from a light source [1,6]. This method is very well suited for molecular fingerprinting, since the absorption versus applied light energy/wavelength is uniquely dependent on the exact molecular structure. The measurement, in which light of various wavelengths is applied, to map the molecular absorption, is referred to as photoacoustic spectroscopy (PAS). Current PAS instrumentation utilizes state-of-the-art conventional microphone technology in combination with high powered light sources to maximize the sensitivity of the system. It is well known from literature (such as [2]), that electrostatic, or capacitive, microphones have the highest sensitivity and the lowest self-noise of the known detection principles. While conventional capacitive microphones provide excellent signal-to-noise ratio, there is a significant problem with vibration-borne artifacts. The vibration sensitivity of the microphone is directly linked to the mechanical sensitivity and mass of inertia of the pressure sensing diaphragm. In the following, we shall demonstrate that the utilization of MEMS technology allows the implementation of microphone structures in which the diaphragm will have very high mechanical sensitivity, while at the same time having a much smaller relative mass of inertia when compared to conventional devices.

*mpedersen@comcast.net

2. THEORY OF OPERATION OF THE CAPACITIVE MICROPHONE

2.1 Quasi static behavior

While the exact behavior of a capacitive microphone depends on the details of the mechanical structure, we shall first enumerate a number of general equations that describe the overall generalized behavior of the device. A general drawing of a capacitive MEMS microphone comprising a pressure sensitive diaphragm and fixed perforated back plate is shown in figure 1 below.

Firstly, the open-circuit electrical sensitivity S_e of the microphone is given by:

$$S_e = \frac{V_b}{h_{a,eff}} S_m, \quad (1)$$

in which V_b is the applied DC bias voltage between diaphragm and back plate, $h_{a,eff}$ is the effective air gap between diaphragm and backplate, and S_m is the mechanical sensitivity of the diaphragm. The DC bias voltage is applied to the microphone from an external source, and the change in microphone capacitance due to a deflection of the diaphragm is usually detected with a transconductance amplifier, as shown in figure 2.

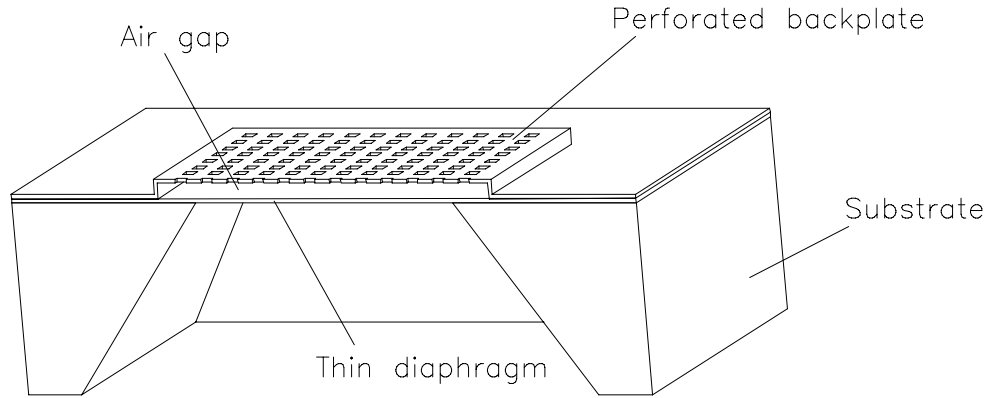


Figure 1: Cross-sectional view of a typical single chip capacitive microphone.

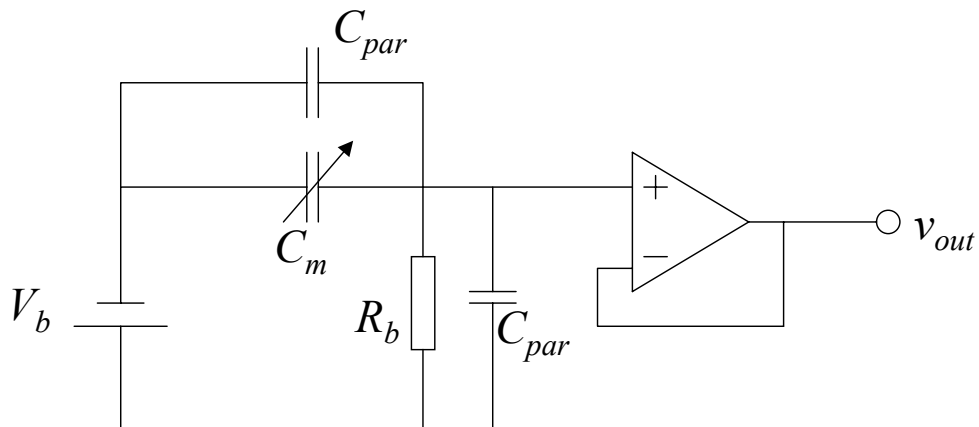


Figure 2: Typical capacitive microphone detection circuit with external DC bias voltage and buffer amplifier.

The capacitive microphone is shown as the variable capacitance C_m in figure 2. Also important are the parasitic capacitances C_{par} that must be kept small, since they will load the high impedance output of the microphone. The resistor R_b represents any leakage current in the amplifier, and must be present to establish the DC bias voltage across the microphone element. The value of R_b must be chosen such that the corner frequency of the high-pass filter formed by C_m (and C_{par}) and R_b is much lower than the lowest acoustical frequency of interest. The static microphone capacitance C_m is given by:

$$C_m = \frac{\epsilon_0(1-k_h)A}{h_{a,eff}}, \quad (2)$$

where ϵ_0 is the permittivity of air, k_h is the hole fraction in the perforated back plate, and A is the overlapping area of the diaphragm and backplate. In the simple equation (1), it is assumed that the motion of the diaphragm is that of a piston. In almost all microphone designs, this is not a valid assumption. A first order method to describe the equivalent piston motion of a diaphragm with confined edges would be to find the volume displacement of the diaphragm in question and define the average (piston) displacement of the diaphragm. The approximate mechanical sensitivity of any diaphragm is hence given by:

$$S_m = k_{d,vol} S_{m,max}, \quad (3)$$

where $S_{m,max}$ is the maximum sensitivity in the center of the diaphragm, and $k_{d,vol}$ is a volumetric reduction factor that depends on the exact diaphragm shape and confinement. If there is any intrinsic tensile stress in the diaphragm, it will reduce the maximum sensitivity of the diaphragm, and affect the volumetric reduction factor.

We shall now discuss a specific microphone design, which pertains to a device developed Knowles Electronics [7]. The device, shown in figure 3 below, comprises a highly perforated back plate formed on a substrate and a diaphragm loosely confined between the substrate and an indentation in the back plate. The loose confinement of the diaphragm serves to eliminate any intrinsic stress in the diaphragm, to maximize the mechanical sensitivity of the diaphragm. The indentation near the perimeter of the back plate helps set the initial air gap in the device and also provide an effective acoustic seal across the diaphragm.

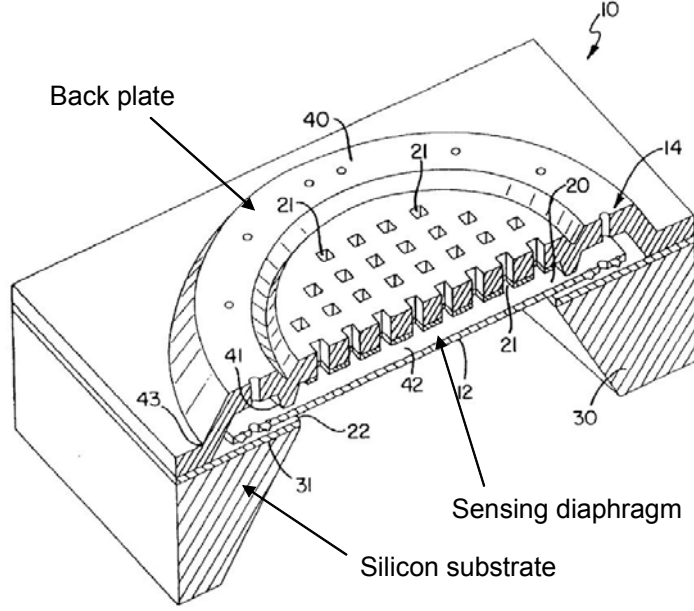


Figure 3: Perspective cut-away view of capacitive microphone structure developed by Knowles Electronics [7].

In operation, a DC bias voltage is applied between the diaphragm and back plate, and the resulting electrostatic attraction causes the diaphragm to move towards the back plate until it makes contact on the indentation at the perimeter of the back plate. After this, the diaphragm itself will deflect further in the center due to the electrostatic attraction force. Once the diaphragm has made mechanical contact at the edge, the boundary conditions will be approximately that of a simply supported plate. The maximum center deflection of a square diaphragm with such boundary conditions can be shown to be [3]:

$$w_{d,\max} = 0.00406 \frac{p a_d^4}{D}, \quad (4)$$

where p is the applied uniform pressure on the diaphragm, a_d is the side length of the diaphragm, and D is the diaphragm rigidity given by:

$$D = \frac{E_d h_d^3}{12(1-\nu_d^2)}, \quad (5)$$

in which E_d , ν_d and h_d are the Young's modulus, Poisson's ratio, and the thickness of the diaphragm. It can also be shown that the volumetric deflection factor for this diaphragm is approximately 0.41, which means the piston-like mechanical sensitivity of the diaphragm is:

$$S_m = 0.41 \frac{w_{d,\max}}{p} = 0.00203 \frac{a_d^4}{D}. \quad (6)$$

As the diaphragm deflects in response to the electrostatic force, the restoring force as defined by the mechanical sensitivity must equal the electrostatic attraction force for the device to be

stable. Otherwise, the diaphragm will be pulled completely towards the back plate, causing a collapse of the structure. The equivalent pressure of the electrostatic force is given by:

$$p_{el} = \frac{\epsilon_0 V_b^2}{2h_{a,eff}^2}, \quad (7)$$

and hence the require force balance between electrostatic and diaphragm restoring forces lead to:

$$\frac{\epsilon_0 V_b^2}{2h_{a,eff}^2} = \frac{h_{a,init} - h_{a,eff}}{S_m}, \quad (8)$$

where $h_{a,init}$ is the initial air gap in the structure set by the lip near the perimeter of the diaphragm. By solving equation (8) for $h_{a,eff}$, it is possible to find the effective air gap in the microphone for any given bias voltage and dimensions:

$$h_{a,eff} = \frac{h_{a,init}}{3} \left\{ 1 + 2 \cos \left[\frac{1}{3} \arccos \left(1 - \frac{27M}{h_{a,init}^3} \right) \right] \right\}, \quad (9)$$

in which M is a parameter given by:

$$M = 0.00203 \frac{\epsilon_0 a_d^4 V_b^2}{4D}.$$

Having derived the equation governing the relationship between effective air gap and applied DC bias voltage, it is also possible to find the critical bias voltage where the collapse of the structure occurs, which is at the point where (9) becomes a complex number. It can be found that the critical bias voltage is given by:

$$V_{crit} = 5.225 \sqrt{\frac{E_d h_d^3 h_{a,init}^3}{(1 - \nu_d^2) \epsilon_0 a_d^4}}. \quad (10)$$

There are different ways to choose an appropriate bias voltage based on the collapse condition. A widely used empirical method is to operate the microphone at a bias voltage of 60% of the critical voltage. This yields a microphone design that is stable in all normal acoustic applications. If one knows the maximum sound pressure $p_{ac,max}$ the microphone will ever be exposed to, it also possible to determine the maximum allowable bias voltage by using the following formula:

$$V_{max} = 5.225 \sqrt{\frac{E_d h_d^3 (h_a - K)^3}{(1 - \nu_d^2) \epsilon_0 a_d^4}}, \quad (11)$$

in which K is given by:

$$K = 0.00203 \frac{p_{ac,max} a_d^4}{D}. \quad (12)$$

The first order resonance frequency of the diaphragm is given simply by:

$$f_{d,res} = \frac{1}{2\pi} \sqrt{\frac{a_d^2}{S_m m_d}} = \frac{h_d}{2\pi a_d^2} \sqrt{\frac{E_d}{0.02436(1-\nu_d^2)\rho_d}}, \quad (13)$$

where ρ_d is the density of the diaphragm material and m_d is the mass of the diaphragm.

For the particular microphone structure shown in figure 3 above, the following material constants can be assumed:

$$E_d = 160 \text{ GPa}$$

$$\nu_d = 0.2$$

$$\rho_d = 2300 \text{ kg/m}^3$$

For photoacoustic applications the sensitivity of the microphone should be maximized over the space of the design parameters. The two most important limitations on parameters due to practical limitations in the microphone fabrication process are:

$$0.5 \text{ } \mu\text{m} < h_d < 2 \text{ } \mu\text{m} \quad (14)$$

$$1 \text{ } \mu\text{m} < h_{a,init} < 4 \text{ } \mu\text{m} \quad (15)$$

If one assumes that the empirical 60% DC bias voltage design rule mentioned above is used, it is possible to compound all equations above into equation (1), yielding the following expression for the open-circuit electrical sensitivity:

$$S_e = \frac{0.09274 a_d^2 \sqrt{1-\nu_d^2} \sqrt{h_{a,init}}}{\sqrt{E_d} h_d^{1.5} \sqrt{\epsilon_0}} \quad (16)$$

In order to evaluate the performance of these microphones, one must select an initial overall criterion, most important to the performance of the microphone in the specific application (in this case photoacoustic instrumentation). One such parameter is acoustic bandwidth, which should be very limited for photoacoustic detection. Typically acoustic frequencies below 500 Hz are of importance. By specifying a certain bandwidth requirement, it is possible, by use of (13), to derive the design relationship between diaphragm size and thickness to meet such a requirement. In figure 4 below, the diaphragm size is plotted versus diaphragm thickness for bandwidths 100, 200, 300, 400, and 500 Hz.

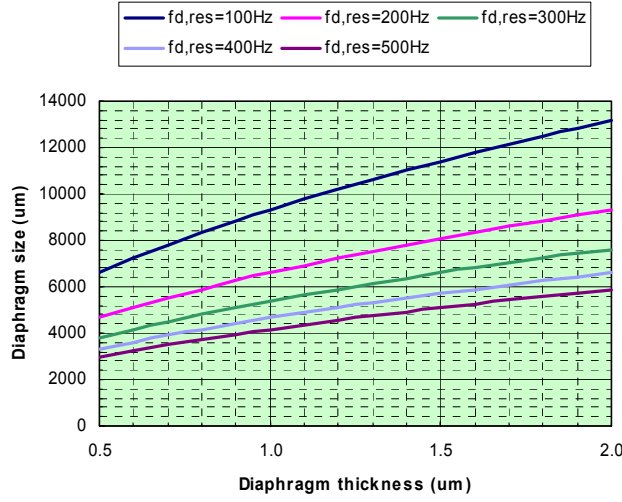


Figure 4: Derived relationship between diaphragm size and thickness for various bandwidth requirements.

In selecting an appropriate diaphragm thickness, the vibration sensitivity of the microphone must be considered. The vibration sensitivity S_v of the microphone for an axial acceleration of 1 m/s^2 , due to the mass of inertia of the diaphragm, is given simply by:

$$S_v = \frac{m_d \cdot 1 \text{ m/s}^2}{a_d^2} = h_d \rho_d \cdot 1 \text{ m/s}^2. \quad (17)$$

It is intuitively clear that one wants select as light, and therefore as thin, a diaphragm as possible to minimize the vibration sensitivity. The calculated vibration sensitivity for a $0.5 \text{ } \mu\text{m}$ thick diaphragm is 1.15 mPa or 35.2 dB SPL . In comparison, the vibration sensitivity for the Brüel & Kjær microphone is specified at 62.5 dB SPL . Hence, an improvement in vibration sensitivity of more than 27 dB can be realized by switching to a MEMS microphone. This is a remarkable improvement over conventional devices, which is also a critical limitation in the current performance and ruggedness of photoacoustic instrumentation in general.

2.2 Dynamic behavior

The dynamic behavior of the microphone is best described using a lumped element parameter model. This form of model is based on the mathematical analogy that exists between the electrical, mechanical and acoustical domains. A good description of this theory can be found in [3]. The basic and most important result of this analogy is that acoustical structures can be modeled with a lumped element simulation tool such as SPICE.

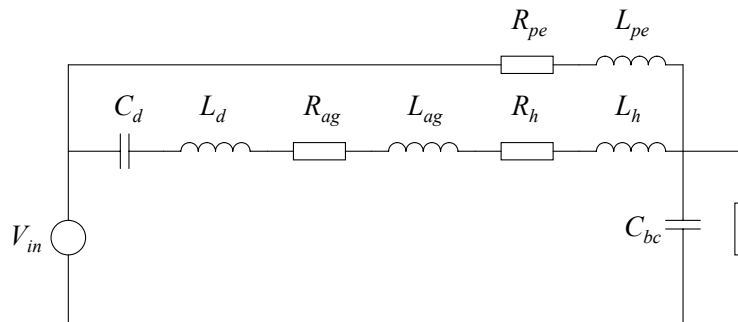


Figure 5: Lumped element acoustical equivalent circuit of MEMS microphone.

The equivalent circuit shown in figure 5 represents all important aspects of the acoustical behavior of the microphone. The only effect that has omitted is the frequency dependent radiation impedance of the diaphragm, which negligible for the diaphragm sizes and acoustical frequencies of interest here. In this circuit, flow through an element represents volume velocity, whereas potential drop represents an acoustic pressure drop over the element. The diaphragm is represented by an acoustical compliance C_d and mass L_d and is assumed to have negligible intrinsic damping. The air in the gap between the diaphragm and the perforated backplate is represented by an acoustical damping R_{ag} due to viscous loss and a mass L_{ag} . The air within the holes in the perforated backplate is represented by another damping element R_h and mass L_h . The back chamber upon which the microphone is mounted also has a compliance C_{bc} which is determined by its size. The elements L_{pe} and R_{pe} represent the mass and viscous loss in the air bypass of the diaphragm. The value of these elements in conjunction with back chamber compliance determines the lower roll-frequency of the microphone. These elements will not be considered in the analysis below. The source V_{in} represents the applied acoustic sound pressure, and the dummy resistor is only included to allow a DC solution of the circuit. All elements in the circuit depend on dimensions of the microphone structure and characteristics of the materials used, and they are defined as follows [5]:

$$C_d = S_m A_d = 0.00203 \frac{a_d^6}{D}. \quad (18)$$

$$L_d = \frac{m_d}{A_d^2} = \frac{h_d \rho_d}{a_d^2}. \quad (19)$$

$$R_{ag} = \frac{12\eta\pi N_h X_0^4}{h_{a,eff}^3 a_d^4} \left[\frac{1}{4} \ln \left(\frac{X_0^2}{r_h^2} \right) - \frac{3}{8} + \frac{r_h^2}{2X_0^2} - \frac{r_h^4}{8X_0^4} \right]. \quad (20)$$

$$L_{ag} = \frac{\rho_0 N_h \pi X_0^4}{h_{a,eff}^4 a_d^4} \left[\frac{1}{4} \ln \left(\frac{X_0^2}{r_h^2} \right) - \frac{3}{8} + \frac{r_h^2}{2X_0^2} - \frac{r_h^4}{8X_0^4} \right]. \quad (21)$$

$$R_h = \frac{8\eta h_b}{\pi r_h^4 N_h}. \quad (22)$$

$$L_h = \frac{4\rho_0 h_b}{3\pi r_h^2 N_h}. \quad (23)$$

$$C_{bc} = \frac{V_{bc}}{\rho_0 c^2}. \quad (24)$$

In these formulas the following new parameters are used:

- η : Dynamic viscosity of air ($18.6 \cdot 10^{-6}$ Ns/m²).
- N_h : Number of acoustic holes in perforated back plate.
- X_0 : Effective distance between holes in back plate.
- r_h : Radius of acoustic holes in back plate.
- ρ_0 : Density of air (1.21 kg/m³).
- h_b : Thickness of back plate.
- V_{bc} : Volume of back chamber (100 mm³).
- c : Speed of sound in air (344 m/s).

If the holes in the backplate are placed in regular square pattern with a center-to-center distance b , the parameters N_h and X_0 can be expressed as [5]:

$$N_h = \frac{a_d^2}{b^2} . \quad (25)$$

$$X_0 = 0.565b . \quad (26)$$

Substitution of these parameters in (20) and (22) yields:

$$R_{ag} = \frac{1.223\eta\pi b^2}{h_{a,eff}^3 a_d^2} B_k , \quad (27)$$

$$R_h = \frac{8\eta h_b b^2}{\pi r_h^4 a_d^2} , \quad (28)$$

$$B_k = \left[\frac{1}{4} \ln \left(\frac{0.319b^2}{r_h^2} \right) - \frac{3}{8} + \frac{r_h^2}{0.638b^2} - \frac{r_h^4}{0.815b^4} \right] . \quad (30)$$

The parameter B_k is called the air gap damping factor, and depends exclusively on the dimensions and distance between the acoustic venting holes in the backplate. The parameter is plotted below in figure 6 as function of b and r_h , in a range useful for the MEMS microphone design in question here.

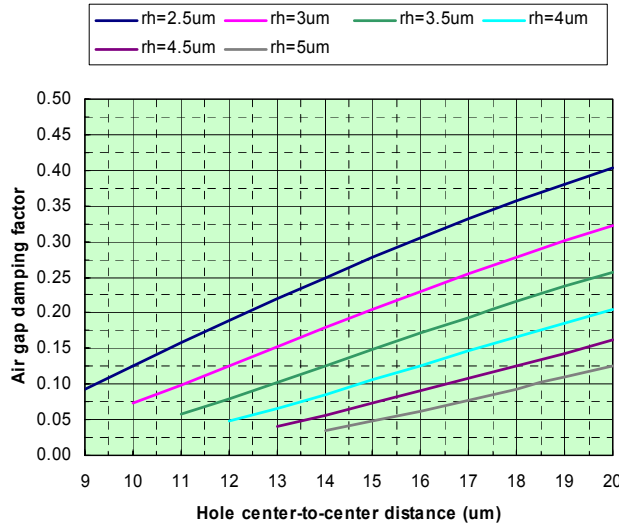


Figure 6: Air gap damping factor for MEMS microphone design.

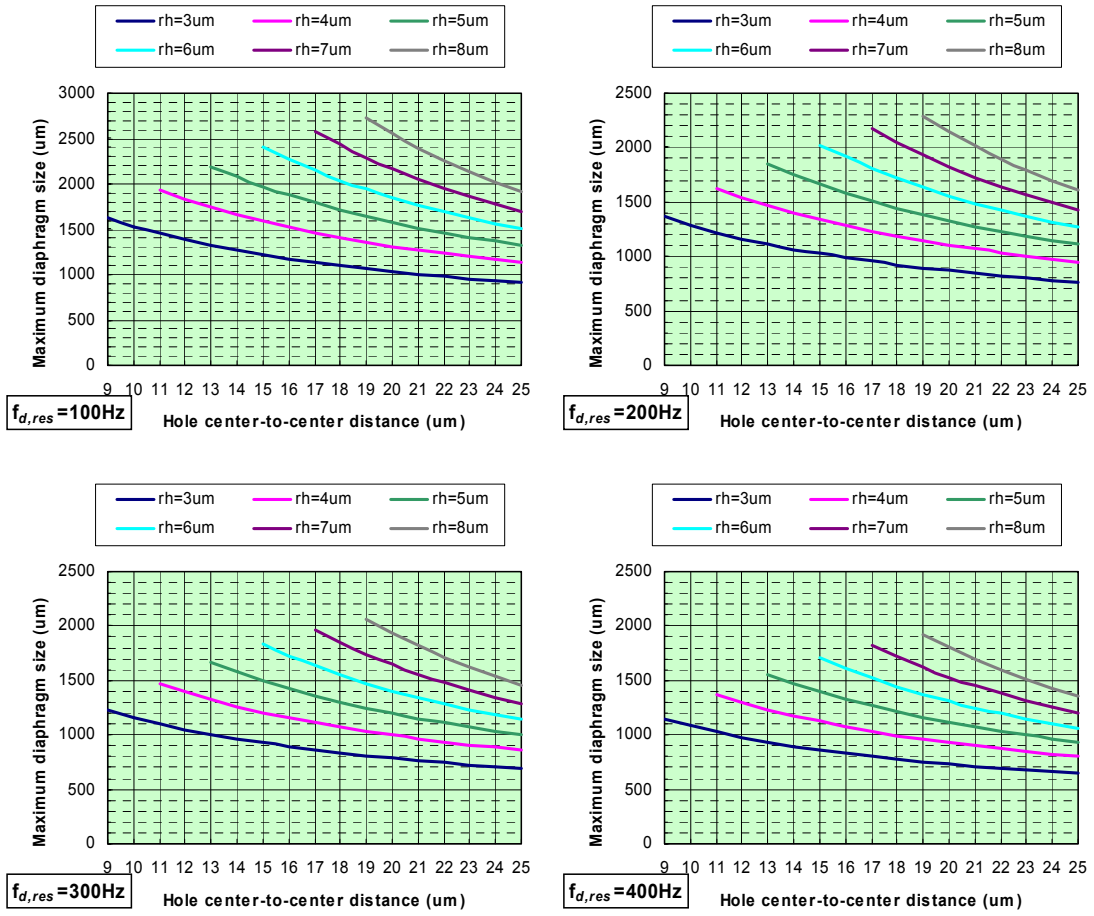
The damping elements R_{ag} and R_h in the circuit are important, as they determine not only the upper roll-off frequency of the microphone, but also the amount of thermal self-noise generated within the microphone structure. Considering the circuit in figure 5, the leakage path to the back chamber R_{pe} and L_{pe} will not add significantly to the overall noise as long as the back chamber compliance is much larger than the diaphragm compliance. Assuming that this is the case, the upper roll-off frequency of the microphone due to damping is given approximately by:

$$f_c = \frac{1}{2\pi C_d (R_{ag} + R_h)} = \frac{r_h^4 h_{a,eff}^3 D}{a_d^4 \eta b^2 (0.03248 h_b h_{a,eff}^3 + 0.004965 \pi^2 r_h^4 B_k)} \quad (31)$$

In addition the acoustic thermal self-noise generated in the microphone is given approximately by:

$$v_{noise,acoust} = \sqrt{4kT(R_{ag} + R_h)\Delta f} = \sqrt{4kT\Delta f \left(\frac{1.223\eta\pi b^2 B_k}{h_{a,eff}^3 a_d^2} + \frac{8\eta h_b b^2}{\pi r_h^4 a_d^2} \right)}, \quad (32)$$

where k is the Boltzmann constant (1.38066×10^{-23} J/K), T is the absolute temperature (300 K), and Δf is the bandwidth of interest.



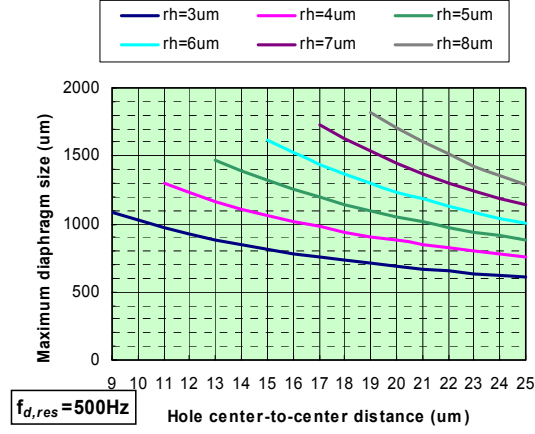
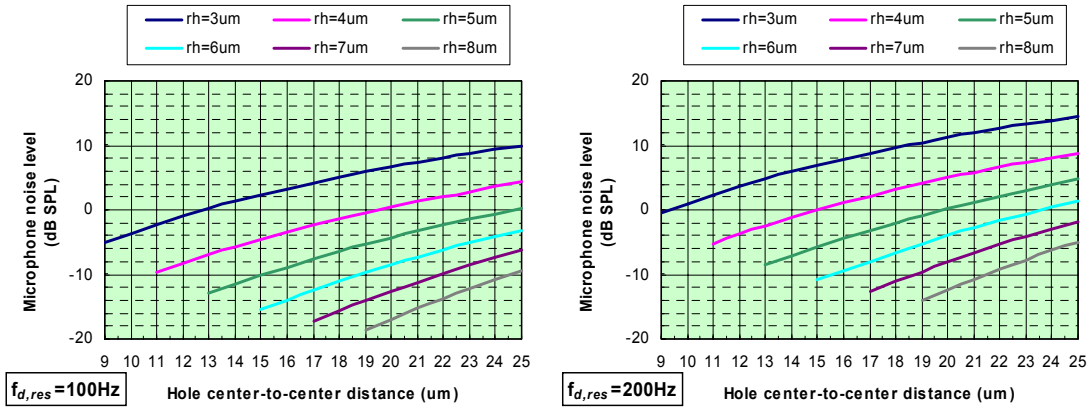


Figure 7: Maximum diaphragm size vs. backplate parameters b and r_h for the various bandwidth requirements.

For photoacoustic applications, an upper roll-off frequency above 500 Hz is sufficient, since most measurements take place in the 10-400 Hz range. Having set this constraint, it is possible to use (31) to calculate the largest allowable diaphragm size a_d for any combination of the back plate parameters b and r_h . The largest possible a_d is desired to reduce the acoustic self-noise in equation (32) as much as possible. Before this can be done, however, one must decide what to do with parameters $h_{a,eff}$ and h_d , which affects the rigidity D . As argued above, a thin diaphragm is desirable as it minimizes the vibration sensitivity of the microphone. From (32), it is clear that an air gap $h_{a,eff}$ as large as possible should be chosen to minimize the acoustic noise in the microphone. Given the limitations (14) and (15), a diaphragm thickness of 0.5 μm and initial air gap $h_{a,init}$ of 4 μm was chosen. Using these constraints, the maximum diaphragm size can be plotted (figure 7) as a function of b and r_h for the different bandwidth requirements.



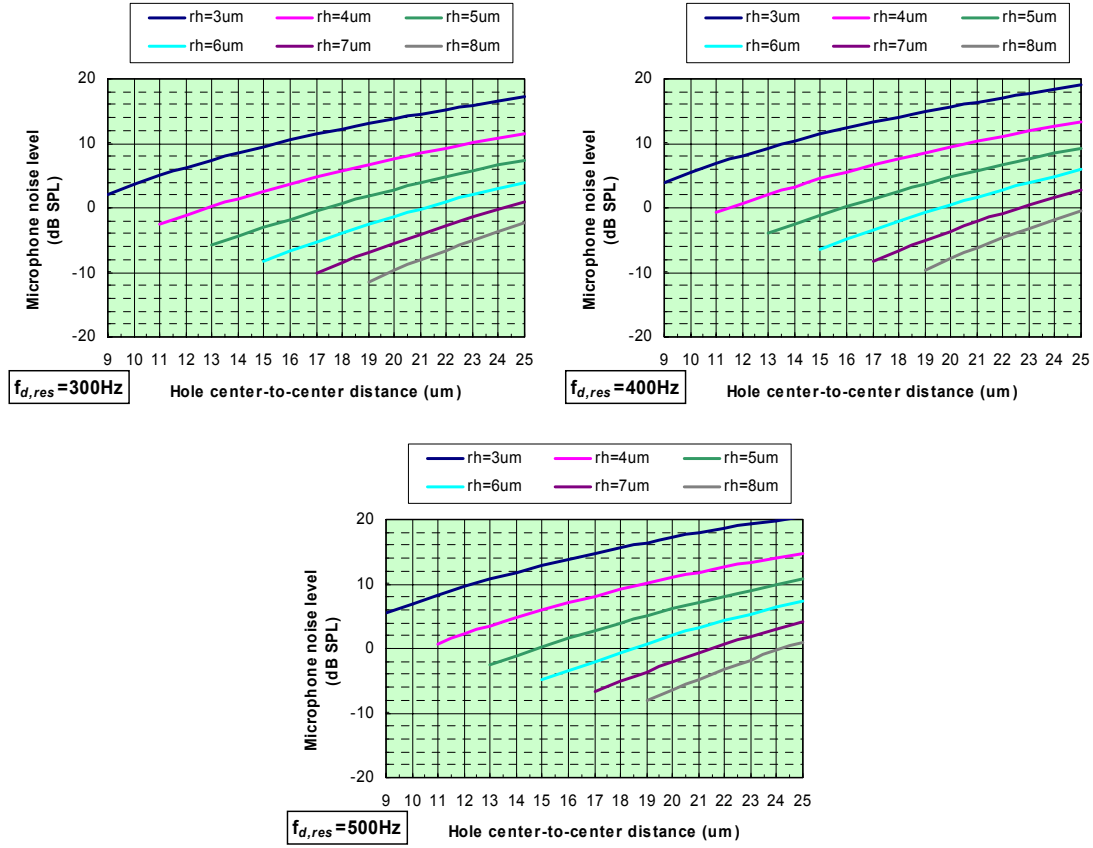
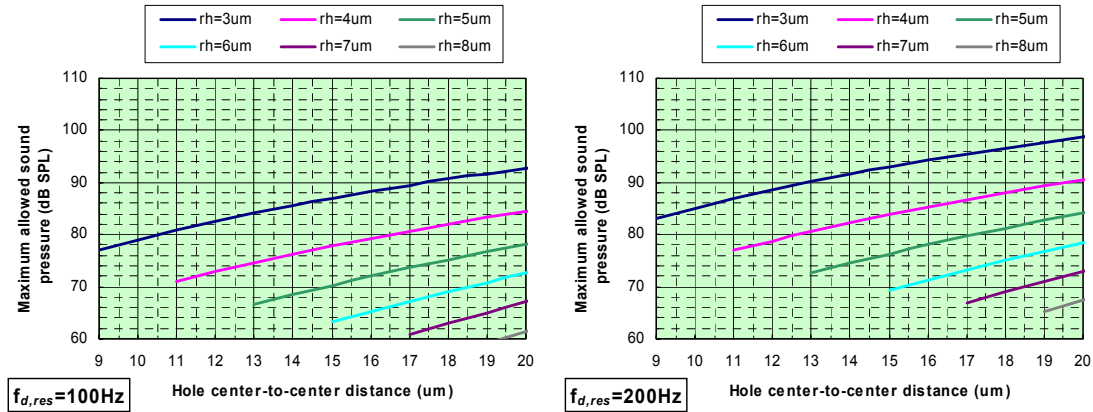


Figure 8: Minimum microphone equivalent noise level vs. backplate parameters b and r_h for the various bandwidth requirements.

The curves in figure 7 indicate the maximum possible diaphragm size allowed to maintain the 100-500 Hz bandwidth of the microphone. Naturally, smaller diaphragms may be used however the acoustic noise will increase for smaller diaphragms. It is now possible to calculate the lowest possible acoustic noise, by inserting the maximum allowed diaphragm size into equation (32). In figure 8 below, the acoustic noise of the microphone is shown in dB relative to the human hearing threshold (20 μ Pa) for the assumed microphone bandwidths.



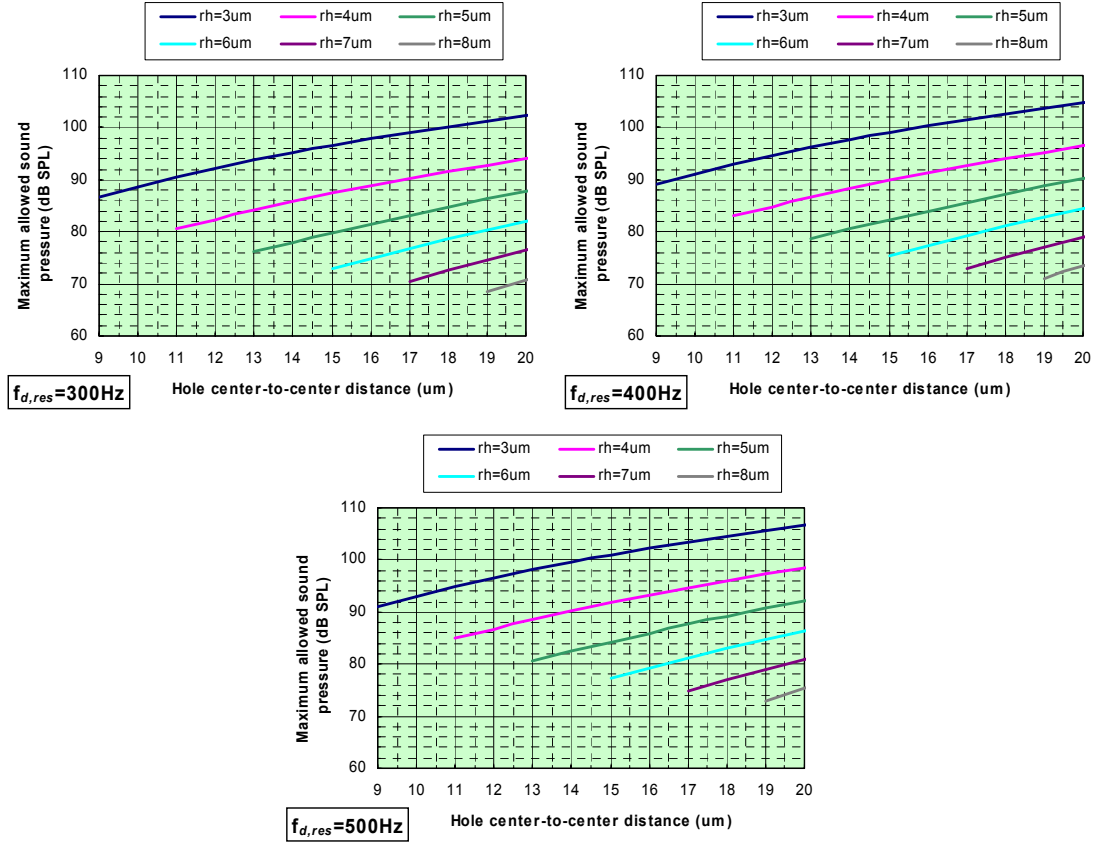


Figure 9: Maximum allowed sound pressure in microphone vs. backplate parameters b and r_h .

With the plots in figure 7 and 8 it is now possible to make an informed decision on the actual dimensions of the device. From figure 8, it is clear that selecting the largest possible vent hole radius with the smallest possible center-to-center distance will give the lowest noise level. To achieve this, however, the size of the diaphragm must be increased according to figure 7. From a fabrication technology standpoint, it is desirable to keep the size of the diaphragm as small as possible. It would seem from figure 7 and 8 that microphone noise levels as low as -15 dB SPL can be realized, depending on the exact bandwidth requirement. This compares very favorably with the conventional Brüel & Kjær 4189 microphone [4], which has a quoted thermal noise level of 15.3 dB SPL. If for instance, a hole radius of $7\mu\text{m}$ and a center-to-center distance of $19\mu\text{m}$ is chosen for a bandwidth requirement of 100 Hz, a diaphragm size of 2.3 mm would yield a microphone with an acoustic self-noise of -14 dB SPL. The required bias voltage can be calculated from (10) and applying the 60% rule, which yields a DC bias voltage of only 0.23 V, which can be easily obtained from any small battery.

A very important limitation on this type of microphone design, however, is the maximum sound pressure which may be applied without causing a collapse of the structure. The sound pressure $p_{ac,max}$ at which this occurs can be estimated to the first order by the following formula:

$$p_{ac,max} = \frac{D}{0.00203a_d^4} \left[h_{a,init} - \sqrt[3]{\frac{V_b^2(1-\nu_d^2)\epsilon_0 a_d^4}{27.30E_d h_d^3}} \right]. \quad (33)$$

This equation does not take into account non-linear stiffening of the diaphragm, which may increase the maximum allowed sound pressure by as much as 6-9 dB, hence it is a worst case

calculation. The maximum allowed sound pressure as function of the back plate parameters is shown in figure 9.

The maximum allowed sound pressure for the MEMS microphone is much lower than that of the Brüel & Kjær microphone, which has a specified maximum sound pressure level of 158 dB SPL. In photoacoustic detection, the upper limit of the acoustic signals generated is still much lower than these numbers, however, during the gas exhaust and injection cycles in the photoacoustic cell, pressure with peaks in excess of 120 dB SPL will routinely be generated. It is therefore, very important that the MEMS microphone is designed to sustain and recover from an inevitable collapse of the diaphragm onto the backplate. The best method to do this is to create mechanical stops that the diaphragm will hit in case of a collapse. The height of the stops is chosen such that they do not interfere with the normal operation of the microphone, and yet prevent the diaphragm from moving beyond the collapse point. It can be shown that the collapse point of the diaphragm in a microphone with a DC bias applied is approximately:

$$w_{d,collapse} = \frac{h_{a,init}}{3}. \quad (34)$$

Therefore, if the height of the mechanical stops is chosen such that w_d is smaller than $w_{d,collapse}$ at all time, the structure is unconditionally stable and the restoring force of the diaphragm will be large enough to pull the diaphragm back off the stops for the microphone to recover. With the information about the diaphragm mechanical sensitivity, it is possible to calculate the acoustic signal range of the microphone, which will be similar to the data shown in figure 9.

The complete results of the microphone calculations are shown in table 1 below and for comparison all relevant specifications of the Brüel & Kjær 4189 capacitive microphone are also listed. It is clear that remarkable improvements of the vibration sensitivity and signal-to-noise ratio can be realized by greatly limiting the acoustic bandwidth of the device. While a redesigned limited bandwidth conventional microphone would produce similar increases in signal-to-noise ratio, there would not be a complementary improvement in vibration sensitivity, due to the fundamental limitations in the technology. This clearly highlights the enormous potential of MEMS microphone technology in photoacoustic applications.

Table 1: Comparison of conventional microphone and MEMS microphone designed specifically for photoacoustic detection.		
	Brüel & Kjær 4189 capacitive microphone [4]	MEMS capacitive microphone of this paper
Diaphragm size	0.5" Ø	2.3 mm
Diaphragm thickness	Unknown	0.5 µm
Diaphragm resonance frequency	14 kHz	820 Hz
Open-circuit sensitivity	50 mV/Pa	2.29 V/Pa
Frequency response	6.3 Hz to 20 kHz ±2 dB	1 Hz to 100 Hz ±2 dB
DC bias voltage	0 V (biased internally)	0.23 V
Microphone capacitance	14 pF	8.15 pF
Thermal noise level	15.3 dB SPL	-14 dB SPL
Maximum sound pressure level	158 dB SPL	65 dB SPL (diaphragm protected by mechanical stops)
Vibration sensitivity @ 1 m/s ²	62.5 dB SPL	35.2 dB SPL

3. SUMMARY AND CONCLUSIONS

In this paper a comprehensive description is given of the design of a MEMS capacitive microphone for photoacoustic instrumentation. Through analytical and numerical calculations, it is demonstrated that a device can be designed with a signal-to-noise ratio superior to that of state-of-the-art conventional microphones, while at the same time reducing the vibration sensitivity of the device by more than 27 dB. Such an improvement promises significant progress in the implementation of rugged, portable, high performance photoacoustic instrumentation for precise chemical and biological detection in the field. The use of MEMS technology allows the implementation of a pressure sensitive diaphragm with dimensions under 3x3 mm that far exceeds the sensitivity of a conventional ½" microphone diaphragm in a much narrower bandwidth suited for photoacoustic instrumentation. Since the bias voltage needed in the MEMS microphone is less than 1 V, the microphone can be easily fed from a small battery, and the sizing of the battery will depend more on the electronic detection circuit included with the microphone element. All simulations in this paper were based on microphone designs implemented in a proprietary MEMS technology.

REFERENCES

8. A. Rosencwaig, *Photoacoustics and Photoacoustic Spectroscopy*, Krieger Publishers, 1990.
9. L.L. Beranek, *Acoustics*, Acoustical Society of America, 1996.
10. S. Timoshenko & S. Woinowsky-Krieger, *Theory of Plates and Shells*, McGraw-Hill, 1970.
11. Brüel & Kjær product data sheet, *The Falcon Range ½" Microphones – Types 4188 to 4193*.
12. M. Pedersen, *A polymer condenser microphone realised on silicon containing preprocessed integrated circuits*, Ph.D. dissertation, University of Twente, The Netherlands, 1997.
13. Brüel & Kjær Technical Review, *Gas Monitoring*, No. 1, 1990.
14. US Patent no. 6,535,460, *Miniature broadband acoustic transducer*.